Effectiveness of Absorber Intercooling for CO_2 Absorption from Natural Gas Fired Flue Gases Using Monoethanolamine Solvent

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Abstract

Chemical absorption using aqueous amine is one of the most feasible options for post-combustion CO_2 capture. One of the main challenges of this technology is its high energy requirements. Absorber intercooling was considered as a viable method to offer benefits in terms of solvent absorption capacity and mass transfer efficiency in CO_2 absorption processes. However, the effectiveness of absorber intercooling on overall energy requirements depends on other factors such as lean loading and liquid to gas ratio. This study evaluates the benefits of using two different configurations of absorber intercooling, i.e. "in-and-out" and "recycled" intercooling when using 30 wt % aqueous monoethanolamine (MEA) to capture 90% CO_2 from a natural gas fired turbine with 4 mol % CO_2. The Lean CO_2 loading was varied from 0.15 to 0.42 (mol CO_2/mol MEA) to determine the lean loading at which the application of intercooling is most significant. Absorber intercooling provides the most benefit at lean loading from 0.30 to 0.34. The use of in-and-out and recycle intercooling at 0.34 lean loading, provided 15.6 and 15.8 % reduction in the total equivalent work associated with 32.0 % and 36.6 % reduction in required packing area when using 1.2 times the minimum liquid flow rate. At lean loading greater than 0.34, the benefit of absorber intercooling is a trade-off between reduction of solvent flow rate and total energy requirement and the drawback of greater packing area in the absorber. The greatest saving in total equivalent work, 17%, was observed at the 0.36 lean loading associated with nearly 60% more packing area when using 1.2 times the minimum solvent flow rate. At very low lean loading and very high lean loading absorber intercooling does not offer significant benefit.

Keyword: Post-Combustion CO_2 Capture, Absorber Intercooling, Energy Efficiency, MEA, In-and-Out Intercooling, Recycled Intercooling,

1. Introduction

CO_2 emissions contribute substantially to global warming. According to the International Energy Agency (1) approximately one third of all CO_2 emissions is the result of fossil fuels combustion to generate electricity. Therefore, the interest in employing techniques to reduce CO_2 emissions from power plants has progressively risen over the past years. Post-combustion CO_2 capture (PCC) from fossil fuel power plants by reactive absorption using amine solvents is the most promising and attractive route, especially since it can be retrofitted existing power plants. The most widely used solvent for chemical absorption is the aqueous solution of 30 wt % monoethanolamine (MEA) (1,2). However, one major disadvantage of this process is its large energy requirement for solvent regeneration. The energy requirement is usually provided by the power plant as steam and electricity, which results in the considerable efficiency loss of the power plant. The addition of an amine-based PCC plant to a natural gas combined cycle power plant leads to a power plant efficiency penalty of 7-11% (3,4). Various alternative process configurations have been proposed to reduce the energy requirements of such processes (5-13).

CO_2 capture by chemical absorption is based on a reversible reaction between CO_2 and a suitable solvent. There are different approaches to save energy in such processes, such as reducing total heating or cooling loads, improving temperature levels of provided coolants or heat sources, or a combination of both (14). One useful method to reduce energy requirements is the application of external coolers to absorber columns (14). Several studies have analysed the effectiveness of absorber intercooling for post-combustion CO_2 capture (PCC) (7-10,12,13,15,16). The use of absorber intercooling in petrochemical industries has proven its effectiveness in lowering overall energy requirements. The effectiveness of using absorber intercooling in terms of energy consumption is dependent on the absorbent and the process configuration (10).

For CO_2 capture, there have been a few studies investigating optimum conditions to use absorber intercooling or identifying process conditions at which intercoolers will be most effective (7,8,10,13). Plaza (7) thoroughly studied the application of simple absorber intercooling for 9 m MEA and 8 m piperazine (PZ) for a range of lean loading with focus only on the absorber, and showed that absorber intercooling is most effective at critical liquid-to-gas ratio, when the temperature bulge without intercooling occurs in the middle of the column. Karimi et al. (10) studied the effectiveness of absorber intercooling for MEA and diethanolamine (DEA) and showed that the best location for intercooling is about one fourth to one fifth of the height of the absorber column from the bottom even if the temperature bulge is closer to the top. Their results showed that the effect of absorber intercooling is more pronounced for DEA especially at low lean loading, while intercooling at high lean loading is better for MEA. Sachde and Rochelle (8) studied the mass transfer benefits of using absorber intercooling for 90% CO_2 capture with 8 m PZ for flue gases with 4 to 27 % mole CO_2. Their study concluded regardless of the flue gas CO_2 the absorber intercooling is most effective when used at intermediate or mid-loading range lean loading, while at extreme loading (either low or high) results showed negligible potential benefits from intercooling. In terms of CO_2 concentration, their findings revealed that intercooling offers the greatest potential when used for 4% CO_2 (gas fired turbine).

To properly evaluate the effectiveness of absorber intercooling, another parameters that will be influenced by the use of intercooling are required to be evaluated as the benefits of using absorber intercooling in majority of operating conditions is a trade-off between solvent rate and packing requirement. Therefore, this study aims to analyse the effectiveness of two types of absorber intercooling, "in-and-out" intercooling and "recycled" intercooling, when using 30 wt. % MEA to remove 90% CO_2 from flue gases with approximately 4 % mole CO_2 for a range of lean loading from 0.15 to 0.42 (mol CO_2/mol MEA) in terms of solvent absorption capacity, absorber packing and overall energy requirement. The CO_2 absorption/desorption process was modelled in Aspen Plus V.8.4 to quantify the solvent flow rate, absorber packing volume, and solvent regeneration energy with and without intercooling for a given lean loading. At each lean loading the optimum location of absorber intercooling was identified by optimising the distribution of absorber packing. The equivalent work concept was used to determine the amount of energy savings with absorber intercooling. Finally the range of lean loading at which the application of absorber intercooling for 30 wt. % MEA is promising was identified, and the lean loading at which the highest savings were obtained was defined.

2. Modelling Framework

The Aspen Plus® RateSep™ model, with capabilities to rigorously model rate-based separations, was used to simulate the absorber and stripper. The model used in Aspen Plus for the thermodynamic properties is based on the work by Zhang et al. (17). The model uses the asymmetric electrolyte non-random-two-liquid (e-NRTL) property method to describe the CO_2-H_2O-MEA chemistry in liquid phase, and the Redlich-Kwong (RK) equation of state for the vapour phase. The model has been validated by Zhang et al. (17) against experimental data available in open literature. In the absorber, the reactions that involve CO_2 were described with a kinetic model. In this model, packed columns were divided into 40 identical segments (stages). For each stage, phase equilibrium, the energy and material balances, heat and mass transfer, and summation equations were determined. Effective interfacial area and liquid side mass transfer coefficients in the absorber column were determined using Bravo-Rocha-Fair correlation for structured packing. An aqueous solution of 30 wt % MEA was used with its proven robustness and popularity in industrial amine scrubbing because of its low cost per mole of amine, high heat of absorption, high rate of reaction and high absorption capacity. The segment model adopted for the absorber simulations was RateSep VPlug flow model, assuming the liquid phase bulk properties in each stage is similar to conditions at which the liquid phase leaves that stage, and the vapour phase bulk properties are the average of the inlet and outlet properties (18). The stripper reboiler section and the absorber intercooler heat exchanger were modelled as equilibrium stages with no reactions involved.

3. Evaluation Methodology

Absorber intercooling was evaluated at lean loading from 0.15 to 0.42. The absorber and stripper were modelled using structured packing and cylindrical columns. Unless otherwise stated, the packing was assumed to be Mellapak 250Y (19). Absorber simulation with and without intercooling was performed at flue gas conditions presented by Rezazadeh *et al*. (20) for 650 MW gas fired combined cycle power plant as presented in Table 1.

Table 1. Flue Gas Composition

Component	Composition (mole %)
N_2	74.39
O_2	12.37
CO_2	3.905
H_2O	8.434
Ar	0.8952

The stripper packed height was over-specified at 20 m, resulting in a pinch in all cases. Noting that a practical design of the stripper column would use an optimised packing height, over-specification of the stripper packed height in this study confirms the packing was being equally utilised in all cases, without additional height optimization criteria, while each case approached equilibrium, and therefore providing an appropriate estimate for the energy requirement. To retain a constant compression work, the stripper operating pressure was kept constant at 170 kPa (1.7 bar) in all load cases.

For an intercooled absorber column, there are three degrees of freedom for optimisation: lean loading, liquid-to-gas (L/G) ratio, and the absorber packing volume. Lean loading and therefore the L/G ratio were varied while maintaining the CO_2 removal constant. Furthermore, at each lean loading the absorber packing volume was minimized by varying the height of the packing sections above and below the intercooling. Results were normalized by the moles of CO_2 removed. Lean solvent and flue gas inlet temperatures were 40°C in all cases. The absorber column diameter was calculated to provide a 75% approach to flooding, and the column height was determined to satisfy 90% CO_2 removal in all cases. Benefits of two different types of intercooling were investigated: “in-and-out” intercooling (simple intercooling) and “recycled” intercooling (advanced intercooling).

Process flow diagrams (PFD) of an absorber column with simple and advanced intercooling are shown in Figures 1 and 2, respectively. In simple intercooling the semi-rich solvent exits the absorber column at the end of one packing section and passes through an external heat exchanger (cooler) to cool down to the temperature at which the lean solvent first enters the absorber column at the top, and then returns to the column at the top of the successive packing section.

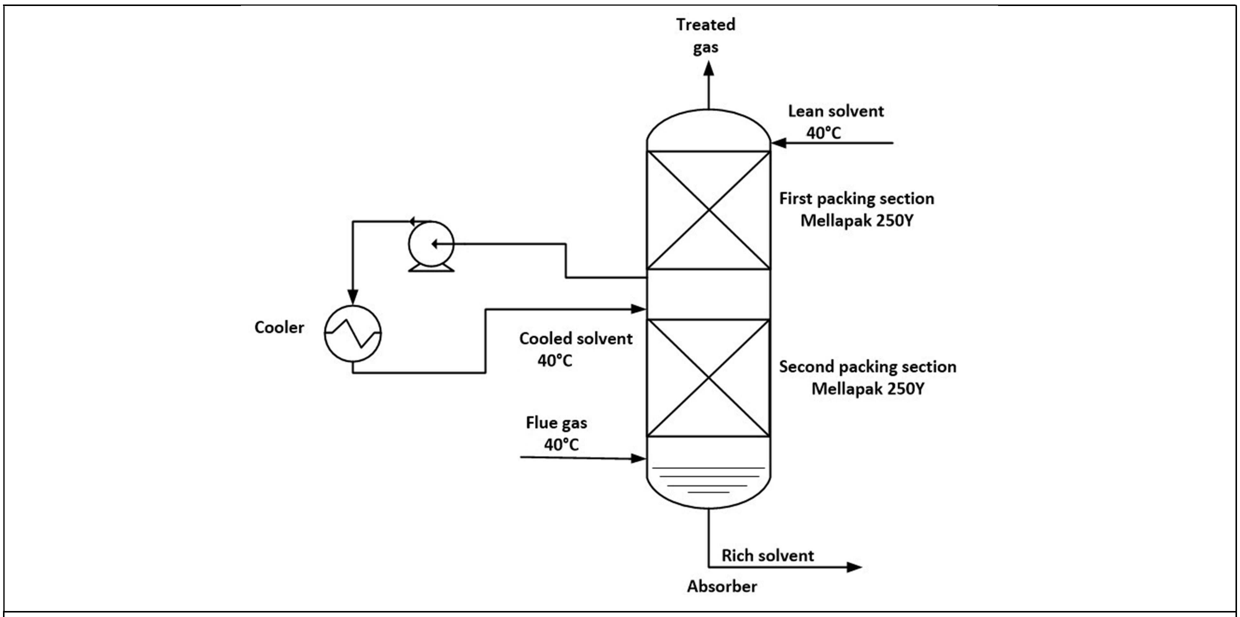

Figure 1. The arrangement of an absorber column with in-and-out (simple) intercooler

With advanced intercooling, the semi-rich solvent is extracted below a middle section of packing, cools in an external cooler to the temperature at which the lean solvent first entered the absorber column at the top, and returns back to the column at the top of the middle section. In this configuration, the absorber packed column was divided into three sections, by which the first and third sections were packed with the Sulzer Mellapak 250Y structured packing, and the middle section (recycled section) with a coarse structured packing, Sulzer Mellapak 125Y, to avoid excessive pressure drop due to the high solvent load in in the middle section. In essence, this is a modification of simple intercooling where the cooled semi-rich solvent recycles around the middle section. The recycle rate is usually 2 to 5 times the solvent flow rate (8) which can be optimised with respect to the operational costs for running the recycled pumps and the absorber flooding.

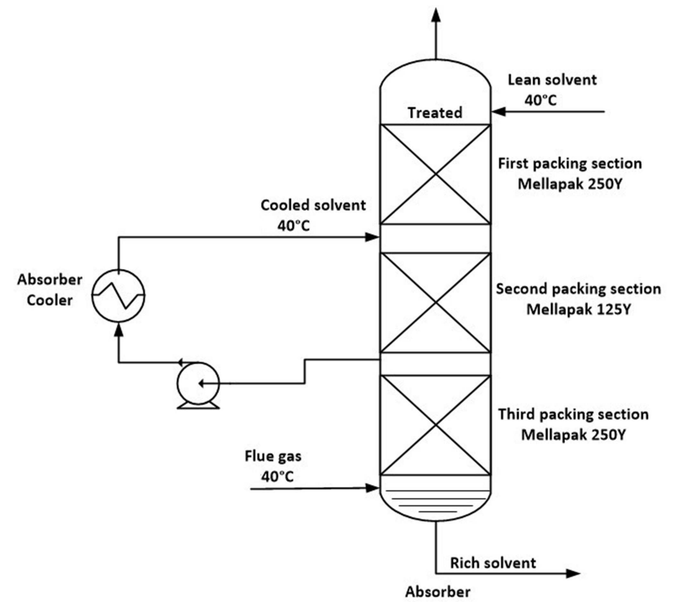

Figure 2. The arrangement of an absorber column with recycled (advanced) intercooling

To find a proper recycle ratio, various recycle ratios, from 1 to 9 times the solvent flow rate, were compared with each other and with the base case, a simple absorber with no intercooling (no recycle rate). As shown in Figure 3 the recycle ratio of 3 was selected as the optimum ratio for natural gas applications with 30 wt % MEA .

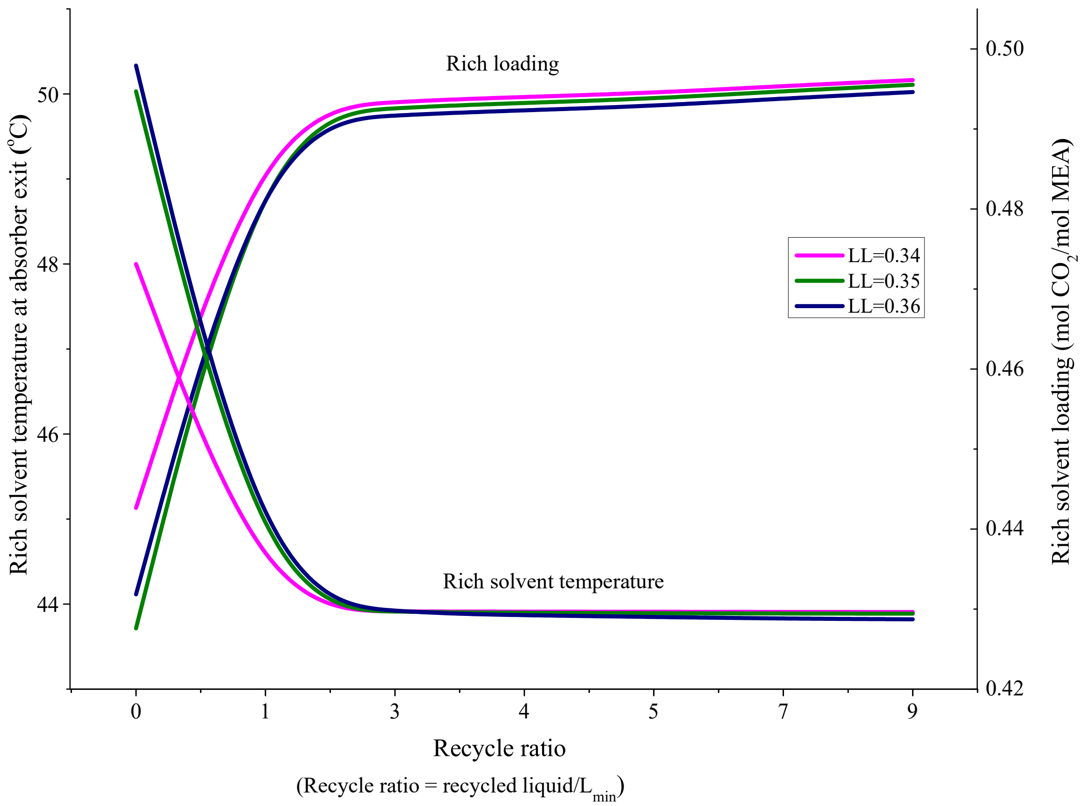

Figure 3. Variation of rich solvent loading and temperature at absorber exit with cooling solvent recycle rate

3.1. Overall energy requirement

Total equivalent work was used to evaluate the overall energy requirement with and without absorber intercooling. This value estimates the total electrical work penalty from the power plant by operating the stripper, compressors and pumps. The total equivalent work (W_{eq}) is calculated as the sum of the regeneration heat equivalent work (W_{heat}), compression work (W_{Comp}), and pump work (W_{Pump}), as shown in Eq. (1) (21).

$$W_{eq} = W_{heat} + W_{comp} + W_{pump} \tag{1}$$

The regeneration heat would draw steam from the steam turbine of the power plant that would be otherwise expanded in low pressure steam turbines to generate electricity (22). Oyenekan (21) suggested calculating the equivalent electrical penalty (work) associated with the heat required for solvent regeneration using the Carnot efficiency, as expressed in Eq. (2).

$$W_{heat} = \eta_{effective} \left(\frac{T_{reb} + \Delta T - T_{sink}}{T_{reb} + \Delta T} \right) Q_{reb} \tag{2}$$

Where, $\eta_{effective}$ is the turbine effective efficiency, T_{reb} is the solvent temperature at the reboiler, ΔT is the temperature difference between hot and cold streams at the reboiler, T_{sink} is the cooling water temperature, and Q_{reb} is the reboiler heat duty. Assumptions made for Eq. 2 include a 90 % efficiency to account for non-ideal expansion in steam turbines (23), an approach temperature of 5 °C for the steam side in the reboiler section, and a sink temperature of 40 °C.

The compression work is the work to compress the captured CO_2 from the stripper pressure (P_{in}), to the storage pressure, e.g. 15 MPa (150 bar), and was calculated using Eq. (3) (24,25).

$$W_{comp} = -3.48 \ln(P_{in}) + 14.85, \qquad 1 < P_{in}\,(bar) < 20 \tag{3}$$

Assumptions made for Eq. (3) include a compression ratio of 2 or less for each compression stage, a compressor polytropic efficiency of 86 %, inter-stage cooling to 40 °C with knocked out water between stages with zero pressure drop (24).

For the absorber with no intercooling, the pump work includes the required head at the efficiency of the pump, 75%, to move and circulate the solvent from absorber to the pressure of stripper and vice versa. For the absorber with simple and advanced intercooling, the work required to pump the cooling solvent from the absorber to the external cooler and back to the column is added to the pump work. The flue gas blower work is excluded. The Aspen Plus pump block is used to calculate the pump work.

4. Results and discussion

4.1. The effect of absorber intercooling on minimum solvent flow rate (L_{min})

For a given lean loading and CO_2 removal, the solvent flow is a function of packing area. By increasing the packing area, the liquid flow decreases until it reaches its minimum value. Figure 4 shows L_{min} to achieve 90% CO_2 removal for a range of lean loading from 0.15 to 0.42 for the three absorber cases: (1) no intercooling, (2) simple intercooling, and (3) advanced intercooling. With no intercooling, L_{min} was determined with 40 m of absorber packing to assure equilibrium pinch at the rich end of the column (26), provided the fractional approach to flooding was held at 75%. Similarly, for absorbers with simple and advanced intercooling, for a given lean loading, L_{min} to achieve 90% CO_2 removal was determined 30 m of packing in each section with 75% flooding fraction.

The effectiveness of intercooling can be better realised by comparing L_{min} at any given lean loading in relation to the theoretical minimum solvent flow rate required at that lean loading to attain 90% CO_2 removal rate. The theoretical minimum solvent flow rate ($L_{isothermal}$) was determined assuming an isothermal absorber where the temperature of the liquid phase throughout the column is the same and equal to the inlet liquid temperature (ideal intercooling) (26). As shown in Figure 4, the lean loading range at which the application of intercooling is promising is equal to and higher than 0.30 as the $L_{min}/L_{isothermal}$ ratio increases by increasing lean loading. The $L_{min}/L_{isothermal}$ ratio at lean loading below 0.30 is close to one, so absorber intercooling would not be helpful in this range. This figure also indicates the minimum ratio is related to the advanced intercooling option suggesting its better performance compared to the simple intercooling option. The highest reduction in the minimum solvent flow rate offered by the simple and advanced intercooling were observed at lean loading of 0.35 with 42.4% and 46.1% reduction when compared to the non-intercooled option, respectively.

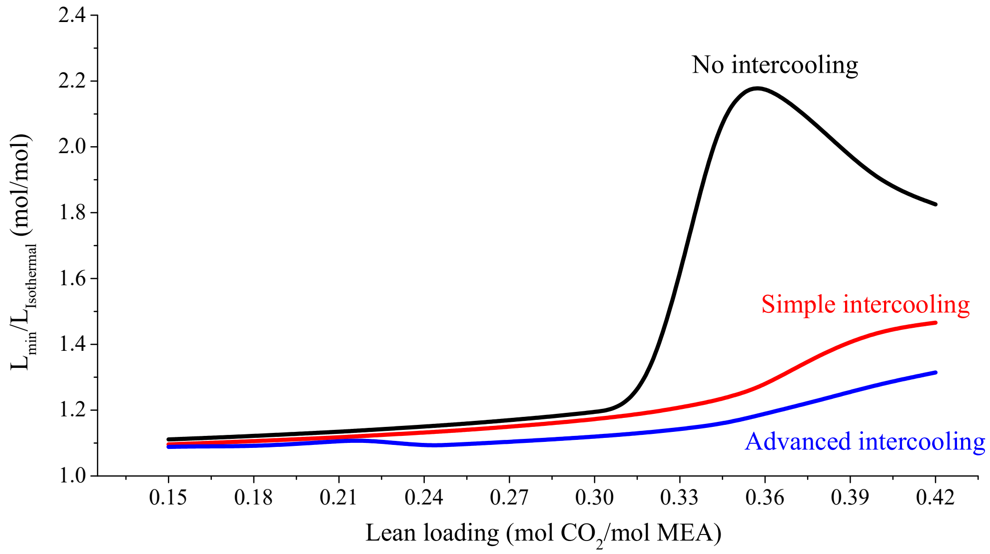

Figure 4. The ratio of minimum solvent flow (L_{min}) rate of simple absorber with no intercooling (black), an absorber with simple intercooling (red) and an absorber with advanced intercooling with the recycle rate of $3xL_{min}$ (blue) to the isothermal solvent flow rate over a range of lean loading

Figure 5 compares L_{min}/G with no intercooling, simple intercooling, and advanced intercooling.

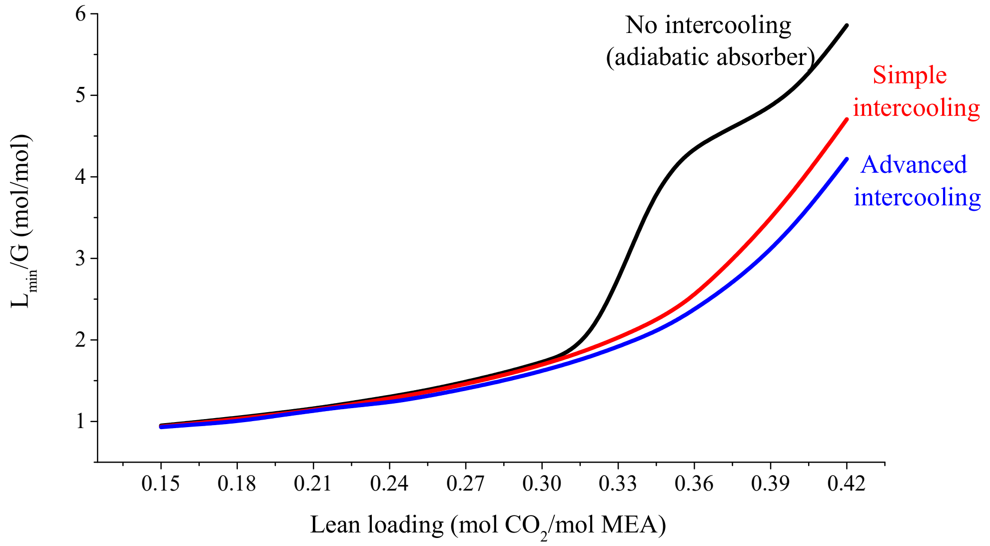

Figure 5. Comparison of minimum liquid to gas ratios (L_{min}/G) of an adiabatic absorber (black), an absorber with simple intercooling (red), and an absorber with advanced intercooling with the recycle rate of $3xL_{min}$ (blue) over a range of lean loading.

4.2. The effect of absorber intercooling on temperature bulge

The aqueous solvent enters the absorber column at the top and counter-currently contacts the flue gas. As the solvent absorbs the CO_2, its temperature increases and causes water to vaporise. Toward the top of the column, the produced water vapour condenses by contacting counter-currently the cooler solvent, which leads to formation of a pronounced temperature bulge in the gas and liquid temperature profiles (27). The magnitude and location of the temperature bulge depends on the solvent lean loading and L/G. Figure 6 shows the magnitude of bulge temperature (T_{Bulge}) for a range of lean loading for an absorber with no intercooling, with simple intercooling, and with advanced intercooling.

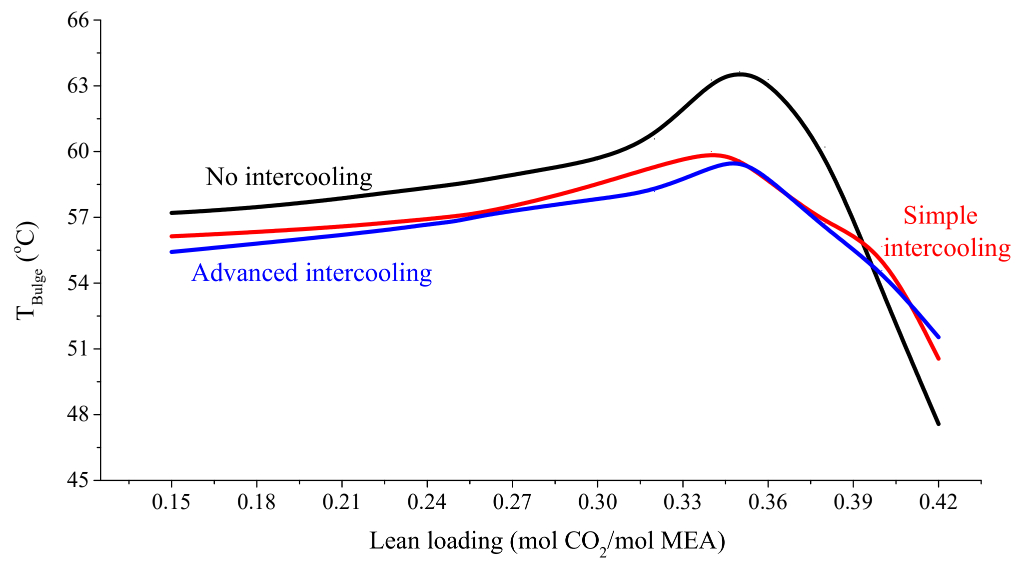

Figure 6. Magnitude of bulge temperature (T_{Bulge})for an absorber with no intercooling (black), with simple intercooling (red) and with advanced intercooling with the recycle rate of 3xLmin (blue) over a range of lean loading.

Figure 7 shows the location of bulge in relation to the absorber column height. As L/G increases, the location of the bulge moves toward the bottom of the column and its magnitude decreases as more heat has been carried by the solvent due to its relatively higher heat capacity. As shown in Figure 6, at low lean loading (0.15 < lean loading < 0.30), the bulge occurs at the top of the packed column. As lean loading and therefore L/G increases, the location of the bulge moves toward the bottom of the column. The slope of move is more pronounced for the absorber with no intercooler. Concurrently the magnitude of bulge temperature ascends by which the greatest temperature bulge occurred at the lean loading of 0.35 in all three cases. After this point, as lean loading increases, the magnitude of temperature bulge descends. The temperature bulge at its peak is located near the middle of the column (H_{Bulge}/H_{total}=0.6) in an absorber with no intercooling, while for the absorber with simple intercooling and advanced intercooling, the temperature bulge at its peak occurs near the top of the packed column, (H_{Bulge}/H_{total}=0.925) and (H_{Bulge}/H_{total}=0.95), respectively.

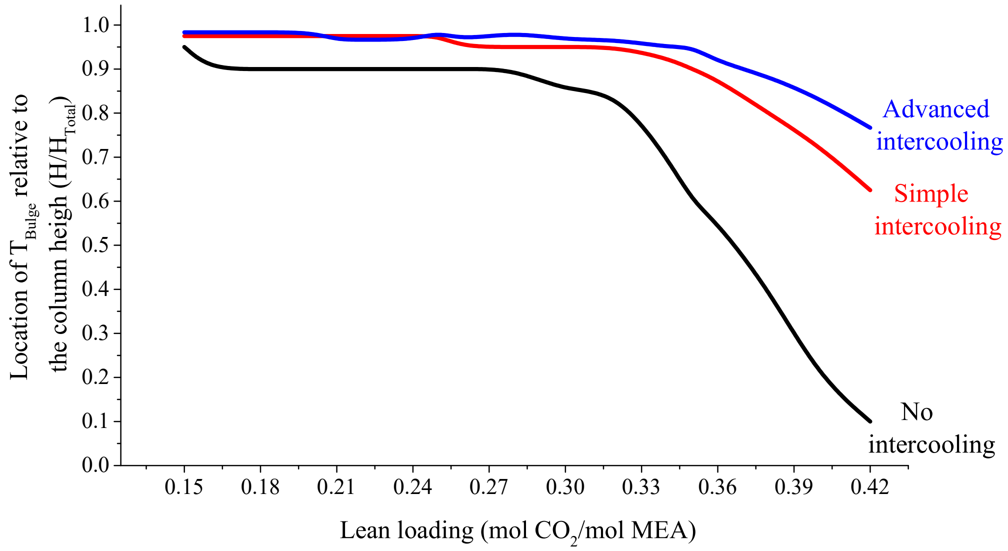

Figure 7. the location of bulge temperature (T_{Bulge}) in relation to the column height for an absorber with no intercooling (black), with simple intercooling (red), and advanced intercooling with the recycle rate of $3xL_{min}$ (blue).

Absorber performance is set by keeping the rich solvent fully saturated and using the solvent flow rate to maintain the desired removal rate. Such an absorber is called rich-end pinched (26). However, at higher L/G ratios, there is excess solvent relative to the inlet gas, therefore fully saturated rich solvent could not be kept, such an absorber is called lean end pinched (27). According to the T_bulge theory (27), the greatest absorption rate will occur away from pinch and so does the temperature bulge. Therefore, as long as the temperature bulge occurs away from the equilibrium pinch, its effect on the column mass transfer is negligible. As can be observed from Figures 5 and 7, for the absorber with no intercooling, at lean loadings between 0.32 and 0.36, the sharp rise in L/G coincides with the location of temperature bulge being near the middle of the column.

Curves related to simple and advanced intercooling shown in Figures 6 and 7 confirm the use of absorber intercooling changes the location and the magnitude of the temperature bulge. The maximum bulge temperature after incorporating simple and advanced intercooling dropped to 60.0°C and 59.6°C respectively, compared to 63.6°C without intercooling. Concurrently, employing absorber intercooling favours the column mass transfer efficiency by moving the temperature bulge to the top of the column. The location of temperature bulge moves to 0.925 and 0.950 of the total absorber packed height, when simple and advanced intercooling were applied, respectively, compared to 0.60 in the non-intercooled case.

In an absorber with no intercooling, when the temperature bulge occurs near or at the middle of the packed column, it is defined as the critical temperature bulge (27) with the critical L/G. In this study, the critical temperature bulge was realised at lean loading of 0.36, with critical L/G of 4.45 (mol/mol). The magnitude and location of the bulge temperature at the critical lean loading are 63.3°C and H_{Bulge}/H_{Total}=0.55, respectively. Figure 8 shows the variation of liquid (rich solvent) and gas (treated solvent) temperatures when leaving the absorber column of the three cases. As shown, both liquid and gas temperature curves display a smoother trend after employing absorber intercooling. The effect of intercooling on the liquid outlet temperature is more pronounced especially in the advanced intercooling case. This is due to the solvent having in general a cooler temperature profile along the absorber column after employing intercooling, which results in an increase in the solvent absorption capacity since the absorption capacity of amine solvents for CO_2 increases with lower temperature. Equally, for a fixed CO_2 removal, absorber intercooling requires less solvent, as shown in Figure 5.

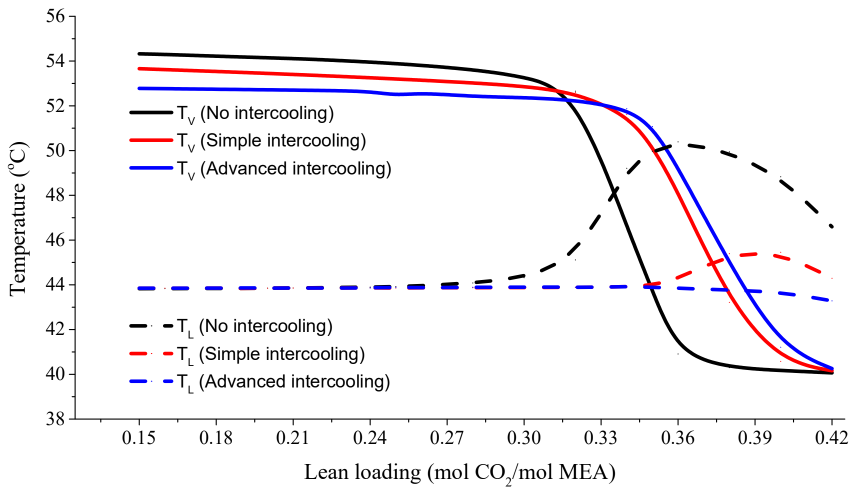

Figure 8. Variations of liquid and gas outlet temperatures over the range of lean loading when operating with minimum solvent flow rate (L_{min}) in an absorber with no intercooling (black), with simple intercooling (red) and advanced intercooling with the recycle rate of $3xL_{min}$ (blue).

4.3. Effect of absorber intercooling on Solvent capacity

Solvent capacity to absorb CO_2 increases as temperature decreases (15). The solvent capacity is defined as moles CO_2 removed per kg lean solvent. Figure 9 shows the variation of solvent absorption capacity with lean loading for the three cases with 90% CO_2 removal. With no intercooling the solvent capacity substantially decreased after a lean loading of 0.32. The rate of solvent absorption capacity reduction is more pronounced from lean loading 0.32 to 0.36. Lean loading 0.36 is the critical lean loading. After the critical lean loading, a slight improvement in capacity was observed due to the excessive increase in the liquid to gas ratio at those lean loading as shown in Figure 5.

Figure 9 shows the change in the solvent capacity when using absorber intercooling. At 0.32 lean loading and above the use of absorber intercooling significantly improves the solvent capacity. At 0.34 lean loading, the use of simple and advanced intercooling provide 75 % and 88 % increase in the solvent capacity, respectively. In general, the solvent capacity decreases with increasing lean loading due to the limiting capacity imposed by the initial high CO_2 content in the lean feed.

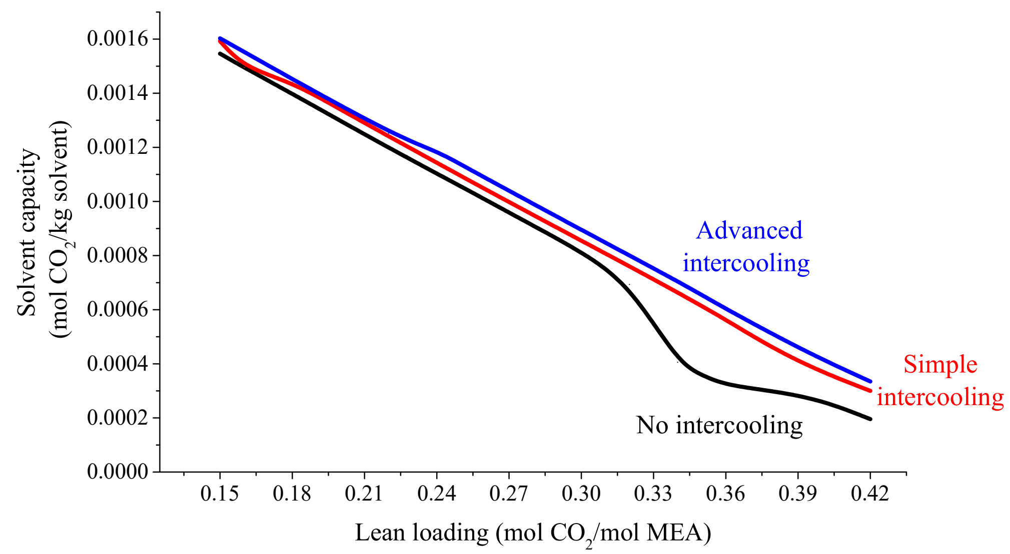

Figure 9. Variation of solvent absorption capacity (mol CO_2/mol solvent) with lean loading for an absorber with no intercooling (black), with simple intercooling (red) and with advanced intercooling with the recycle rate of $3xL_{min}$ (blue)

4.4. Effect of absorber intercooling on rich solvent loading

Figure 10 compares the variation of rich solvent loading with lean loading with no intercooling, simple intercooling and advanced intercooling.

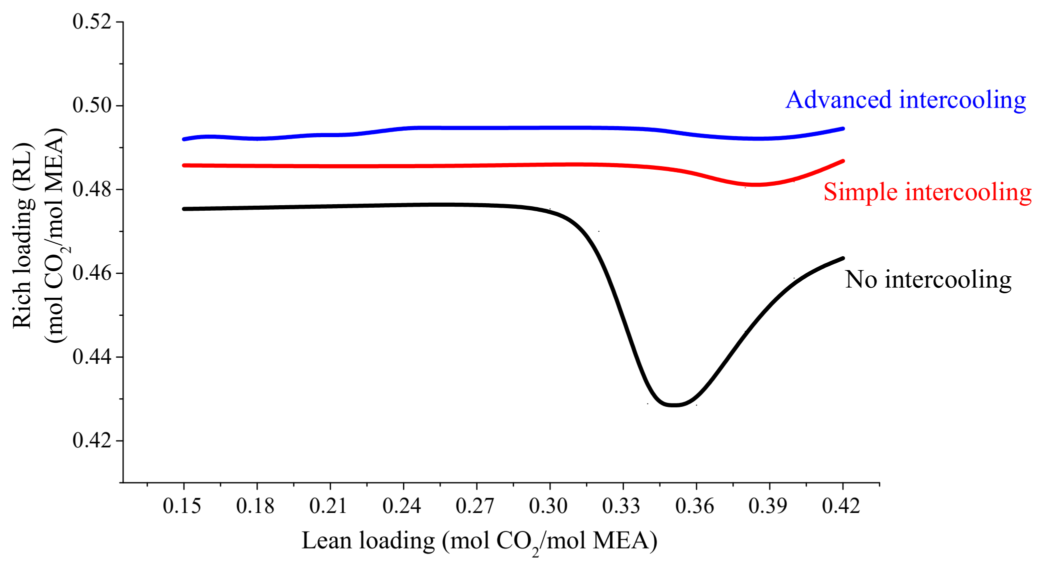

Figure 10. The variation of rich solvent loading with lean loading for an absorber with no intercooling (black), with simple intercooling (red) and with advanced intercooling with the recycle rate of $3xL_{min}$ (blue) when using minimum liquid to gas ratio (L_{min}/G)

By considering Figures 5, 6 and 10 together, the following results can be concluded:

- At lean loading up to 0.30, the rich loading with no intercooling is fairly constant with a steady increase of L_{min}/G with increasing lean loading. Using both simple and advanced intercooling slightly increase the rich loading by 2.0% and 3.8%, respectively, with no noticeable changes in their L_{min}/G. At this range, in all three cases the temperature bulge occurs at the top of the column confirming the use of absorber intercooling would not be helpful.
- At lean loading from 0.30 to 0.36, a noticeable decline in the rich loading coincided with a sharp increase in the L_{min}/G were observed at the absorber with no intercooling. At this range, the temperature bulge occurs near the middle of the column. The difference between the L_{min}/G of non-intercooled and intercooled cases reaches its maximum at 0.34 lean loading. The significant reduction in L_{min}/G and improvement in rich loading by using simple and advanced intercooling confirm the effectiveness of intercooling at this lean loading range. At 0.34 lean loading, the use of simple and advanced intercooling provides 42.0% and 45.6% reduction in L_{min}/G, and 12.4 and 14.5% increase in rich loading, respectively. Also, at 0.34 lean loading, the use of simple and advanced intercooling resulted in 63.5% and 73.6% increase in the solvent absorption capacity, respectively.

- At lean loading higher than 0.36, a gradual increase in the rich loading coincided with continual increase in the L_{min}/G with lean loading observed at the absorber with no intercooling. Due to the limited capacity, the solvent flow considerably increases with lean loading. The use of absorber intercooling slightly reduces the solvent flow yet the rich loading remain almost constant.

As shown in Figure 10, the increase in rich loading by using simple and advanced intercooling confirms that intercooling in general allows the absorber column to have a closer approach to equilibrium. Furthermore, for a given lean loading, the increase in rich loading coincides with another advantage of using intercooling that is less lean solvent flow is required compared to that of no intercooling to achieve 90% CO_2 removal. As shown, the use of absorber intercooling is helpful at medium to high lean loading which is associated with higher solvent flow. The benefit of absorber intercooling at high lean loading should be realised by evaluating the energy requirement for solvent regeneration. This will be discussed in the following sections.

4.5. Application of Absorber intercooling with 1.2 L_{min}

The lean loading range at which the use of absorber intercooling is beneficial when using minimum liquid flow (L_{min}) is roughly from 0.30 to 0.38. The minimum liquid flow to achieve 90% CO_2 removal is determined based on an infinite packing volume, which is not a practical design in terms of plant economics. The optimisation of liquid to gas ratio in terms of plant economics suggests the molar L/G ratio should be about 1.2 to 1.5 times its minimum value in order to avoid using excessive packing (26). Therefore, the solvent flow was set to 1.2 times its minimum flow. Subsequently, the absorber required packing volume, including each section height and diameter, was optimised to provide 90% CO_2 removal.

4.5.1. Effect of absorber intercooling on absorber packing area with 1.2 L_{min}

Figure 11 shows the required packing area to achieve 90% CO_2 removal when using 1.2 L_{min}. The required packing area is calculated by multiplying the volume of packing by the packing specific surface area. For Sulzer Mellapak 250Y and 125Y, the specific surface area is 250 and 125 m^2/m^3

packing, respectively (19). For all cases, the optimum packing volume was calculated by with diameter specified to get 75 % flooding, and adjusting the height to achieve 90% CO_2 removal.

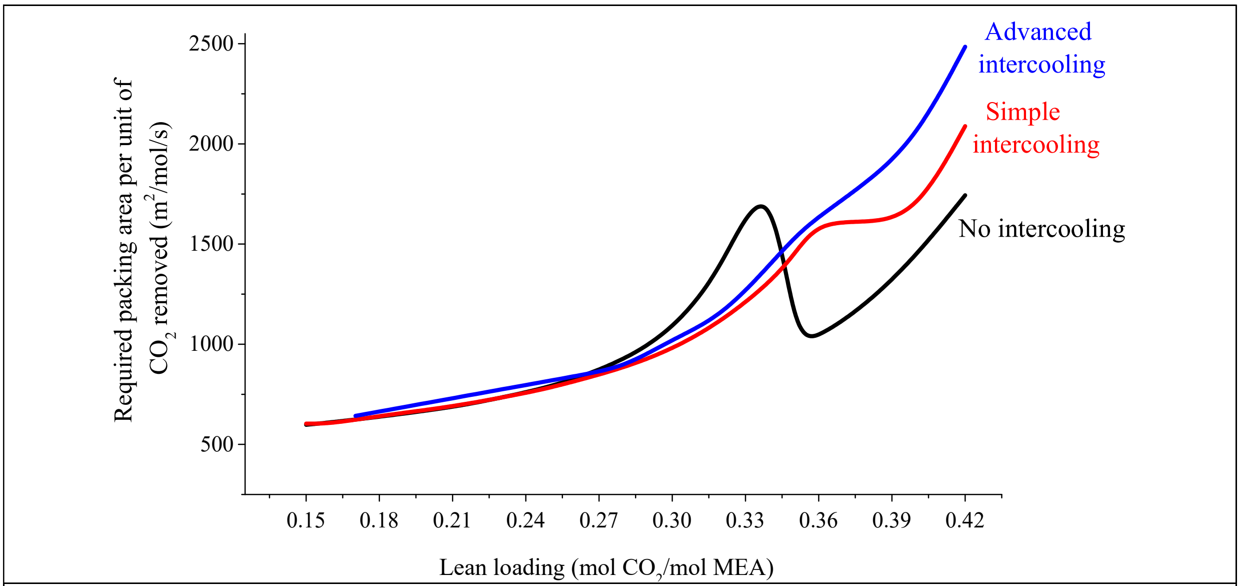

Figure 11. Required packing for an absorber with no intercooling (black), simple intercooling (red), and advanced intercooling with the recycle rate of $3.6L_{min}$ (blue) , $L/L_{min} = 1.2$

As Figure 11 shows, at lean loading from 0.28 to 0.34, the required packing area decreases when using absorber intercooling with 1.2 L_{min}. The greatest reduction in the required packing area was observed at 0.34 lean loading wit 30% and 26% reduction when incorporating simple and advanced intercooling, respectively.

At 0.35 lean loading and above, the use of absorber intercooling resulted in greater rich loading. As Figure 11 shows, additional packing area is required to achieve these benefits. For instance, at 0.36 lean loading, the use of simple and advanced intercooling, results in 43 % and 47 % reduction in the L/G, respectively, which is associated with 60 % and 62 % increase in the absorber required packing area, respectively. At lean loading below 0.30 the use of absorber intercooling does not change the packing requirement.

The absorber required packing areas per unit of CO_2 removed as presented in Figure 11 for a range of lean loading with and without using absorber intercooling were calculated based on using the Bravo-Rocha-Fair correlation to determine the liquid side mass transfer coefficient (k_L) which is the Aspen Plus® suggested mass transfer model to calculate the liquid side mass transfer coefficient for structured packing applications. There is a great deal of uncertainty in calculating the liquid side mass transfer coefficient, and this uncertainty directly impacts the calculation of absorber packing area. The Bravo-Rocha-Fair correlation is a generalised mass transfer model which represents an average of a wide range of hydraulic conditions, packing types/materials, and fluid properties that may not be representative of chemical based CO_2 capture process conditions using amine solvents (28). A new empirical mass transfer model developed by Sachde (28), called the sachde model, to isolate independent variables that impact mass transfer performance and to regress model coefficients from data collected in a pilot scale column operated with structured packing for chemical based CO_2 capture process. The Sachde model is expected to closely represent the packing and hydraulic conditions experienced in the amine-based absorption columns used in CO_2 capture processes. The Sachde model was developed using data collected at the Separation Research Program (SRP) at the University of Texas at Austin (UT) (28).

To put this uncertainty into perspective, for 0.36 lean loading, the liquid side mass transfer coefficient when using simple and advanced intercooling, was calculated using these two models and presented in Table 2.

Table 2. Comparison of the liquid side mass transfer coefficients (k_L) calculated using the Sachde (28) and those using Bravo et al. (1985) at 0.36 lean loading

Method of determining k_L (m/s)	Simple intercooling	Advanced intercooling
Bravo-Rocha-Fair	3.51	4.76
Sachde	1.57	4.78

As shown in Table 2, the liquid side mass transfer coefficient calculated by Bravo-Rocha-Fair model is more than twice that calculated by Sachde when using simple intercooler. The calculation and comparison of the liquid-side mass transfer coefficient using these two approaches, as presented in Table 2, were performed for a part of lean loading range that requires additional packing area to realise benefits of using absorber intercooling. As such, the present work only covers a limited range of process conditions, i.e. those that are potentially industrially relevant. In contrast, investigating the origins of differences between these two approaches would require a very different approach, in which a wide range of process conditions would be investigated, to determine the circumstances in which the two approaches converge, versus those under which divergence between the two approaches takes place and this would be a necessary precursor to drawing a final conclusion on the origins of differences between the estimation of the liquid-side mass transfer coefficient each of these two approaches provides.

Calculations with the Sachde correlation show that at 0.36 lean loading, the use of advanced intercooling results in nearly 14.5% reduction in the required packing area compared to that when simple intercooling was used, while calculations based on the Bravo-Rocha-Fair model show 1.5% more packing area is required when using advanced intercooling than that of simple intercooling.

4.5.2. Effect of absorber intercooling on total equivalent work

Figure 12 shows the total equivalent work of the CO_2 capture process with and without absorber intercooling over the range of lean loading. The compression work was constant across all cases as the stripper pressure was kept at 17 kPa (1.7 bar).

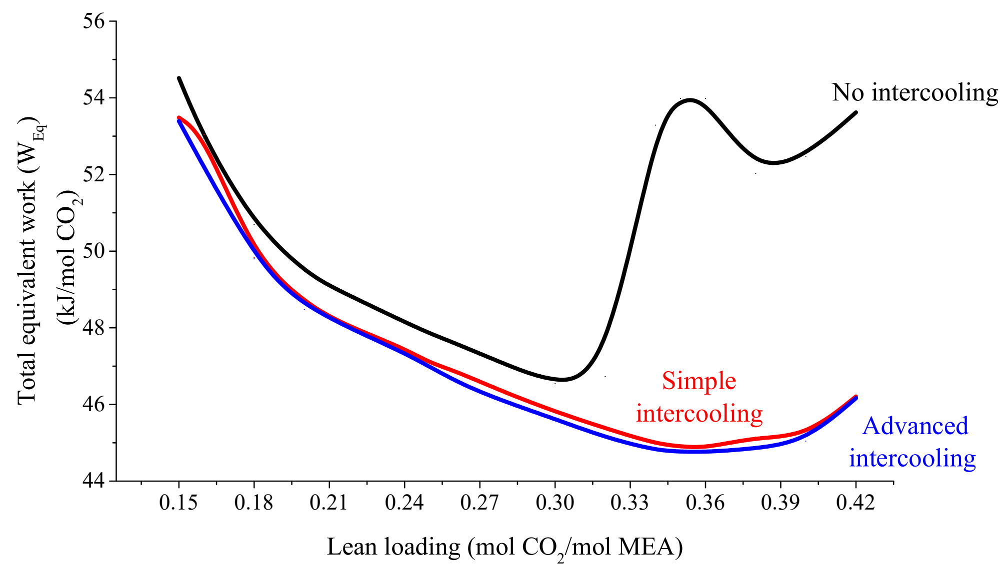

Figure 12. calculated total equivalent work for an absorber with no intercooling (black), with simple intercooling (red), and with advanced intercooling with the recycle rate of 3x1.2xL_{min} (blue) for a range of lean loading, L/L_{min}=1.2

As Figure 12 shows, at 0.30 lean loading and above, the total equivalent work significantly decreases with absorber intercooling. The highest energy saving (17%) was realised at 0.36 lean loading with both simple and advanced intercooling. Figures 5, 11, and 12demonstrate that absorber intercooling at lean loading from 0.30 to 0.34 reduces solvent flow, absorber packing area, and total equivalent work. The use of simple and advanced intercooling at 0.34 lean loading decreases the total equivalent work by 16% with 32 % and 37 % reduction in packing area. At lean loading from 0.30 to 0.34 absorber intercooling is promising and helpful.

With greater than 0.35 lean loading and above, the benefits of absorber intercooling are a trade-off between reduction of solvent flow and total energy requirement and the use of greater packing area in the absorber.

5. Conclusions

Two absorber intercooling configurations were evaluated for CO_2 capture with 30 wt % MEA to remove 90 % CO_2 from gas turbine fired flue gas for lean loading from 0.15 to 0.42. The effect of absorber intercooling on temperature bulge, liquid flow, L/G, rich loading, and solvent capacity were evaluated using minimum solvent flow (L_{min}). Benefits of using absorber intercooling on the absorber packing area and the plant overall energy requirement were quantified using 1.2 L_{min}. The total equivalent work value was used to evaluate the plant overall energy requirement.

At lean loading below 0.30, the temperature bulge occurs near the top of the column and away from the equilibrium pinch at the rich-end with no intercooling, therefore absorber intercooling would not be helpful in this range. Minor reduction in L_{min}/G and total equivalent work with intercooling confirms this conclusion.

At lean loading from 0.30 and 0.36, significant increase in L_{min}/G coincides with sharp reduction in rich loading with no intercooling. In this range, the temperature bulge was around the middle of the column. The use of absorber intercooling showed a positive effect on both L_{min}/G and rich loading. The use of absorber intercooling at lean loading from 0.30 and 0.34 provides reduction in both required packing area and total equivalent work. At 0.34 lean loading, incorporation of simple and advanced intercooling provides respectively 32% and 37% reduction in the required packing area, coinciding with 16%% reduction in the total equivalent work.

At lean loading of 0.35 and above, absorber intercooling reduces L/G, rich loading, and the overall energy requirement. In this range, additional packing is needed at L/L_{min}=1.2 to get these benefits. For instance, at 0.36 lean loading, simple and advanced intercooling provide 43% and 47% reduction in L/G, 17% reduction in the total equivalent work, and 60% and 62% increase in the absorber packing area, respectively.

There is a considerable difference between the calculated value of the absorber liquid side mass transfer coefficient (k_L) when using the Bravo-Rocha-Fair correlation and that determined by the Sachde (28) correlation, resulting in a great difference in the estimated packing area requirement at higher lean loading (0.36 and above) when using simple and advanced intercooling. At 0.36 lean loading, the Sachde correlation with advanced intercooling results in 15% reduction in the required packing area compared simple intercooling, while calculations with Bravo-Rocha-Fair require 1.5% more packing area than with simple intercooling.

These findings can be used as a guideline for future applications of absorber intercooling for commercial scale natural gas fired turbines with 4 mol % CO_2 when using 30 wt % aqueous MEA as solvent.

6. References

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